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A baseline regional evapotranspiration (ET) and change hotspots over Indian sub-tropics using satellite remote sensing data

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ABSTRACT

The annual water loss through evapotranspiration (ET) is an uncertain but significant component of India's water budget. The present study generated independent estimates of baseline annual ET, calibrated with in situ micrometeorological data over Indian sub-continent, using surface energy balance framework and satellite-based long-term thermal remote sensing, visible and near-infrared observations as the primary data sources. Thirty years' (1981–2010) of satellite-based ET estimates at 0.08° grid resolution were used to assess trend in regional ET, to find out change hot-spots and probable causes. Long-term collateral data, influencing ET, such as gridded (0.5° × 0.5°) annual rainfall (RF), annual mean surface soil moisture (SSM) at 25 km resolution from ESA scatterometers and annual mean incoming shortwave radiation from MERRA-2D reanalysis were also analyzed. Mean annual ET loss was found to be the highest for Indian cropland (890 Cubic Km) than forest (575 Cubic Km). Annual water consumption pattern over vegetation systems showed declining ET trend at the rate of -16 Cubic Km yr^{-1} upto 1995 during 30 years which might be due to declining rainfall and solar dimming. This was followed by increasing ET trend (34 Cubic Km yr^{-1}). During 2001–2010, irrigated cropland showed a steep increase in water consumption pattern with an average rate of 4 Cubic Km yr^{-1} while grassland and forest showed declining consumption patterns since 2003 and 2007, respectively thus showing crossover points of their consumption patterns with irrigated cropland. Four agriculturally important Indian eastern, central, western and southern states showed significantly increasing ET trend with S-score of 15–25 and Z-score of 1.09–2.9 during this period. Increasing ET in western and southern states was found to be coupled with increase in annual rainfall and SSM. But in eastern and central states, no significant trend in rainfall was observed though significant increase in ET was noticed. Region-specific correlation of annual ET with natural forcing variables was higher for incoming shortwave radiation as compared to rainfall. The increase in ET over irrigated croplands as well as over some of the Indian states could be due to increase in anthropogenic factors which need more detailed investigations in future.

1. Introduction

Evapotranspiration (ET) provides a link between energy and water budget in hydrological cycle. Estimation of large-scale ET using space-based observations has gained popularity with the advancement in optical and thermal remote sensing. The long term trends of ET and its forcing factors need to be understood and quantified under changing climatic conditions to address water security issues related to water rights, water allocation, crop water use efficiency, human consumption and industrial water use. Several researchers have studied the impact of ET under various climatic settings. Zeng et al. (2012) estimated annual ET over 59 major river basins for 2003–2009 using water balance approach. Where, globally averaged land ET was noticed to be about 604 mm yr^{-1} with a range of 558–4650 mm yr^{-1}. Non-significant trend in global land ET over the last decade were the outcome of this study.

Liu et al. (2013) used dynamic land ecosystem model (DLEM) to simulate ET over a period of 1901–2008 and observed significant decrease in ET over parts of basins of the Gulf of Mexico. Generally, ET decreased in western arid area while increase was observed in eastern part of their study area during the past 108 years. Long term ET was

Abbreviations: NOAA, National Oceanic and Atmospheric Administration; PAL, pathfinder AVHRR land; MODIS, moderate resolution imaging spectroradio meter; AQUA, aqua is the name of satellite initially known as aqua; MERRA, modern era retrospective analysis for research and application; INSAT, Indian National Satellite System; mmyr^{-1}, millimeter/year; ET, evapotranspiration; NFF, natural forcing factors; LULC, land use land cover

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characterized by (Gao et al., 2012) over the Haihe River basin in China for the period of 1960–2002 using the complementary relationship and the Thornthwaite water balance (WB) approaches. The annual ET was found to exhibit decreasing trends in most parts of the Haihe River basin.

Increasing ET over the past 50 years was reported (Walter et al., 2004) for several large basins across the conterminous United States. Though global ET showed an increasing trend in last two decades and no trend in the recent decade, contrasting trends were reported over different countries, river basins or even over different regions within a country. Moreover, most of the above studies have used water balance methods to estimate ET as residual of water budgeting and also the scale of ET estimates through this approach was coarser in nature.

Specific to Indian sub-tropics, there is a knowledge gap in having long-term trend on country-scale and region-specific finer resolution large-scale ET from surface energy balance and thermal remote sensing. The proper attention has not been paid by water resource managers to bring out independent and reliable estimates of baseline climatic annual ET over India's vegetated landmass using surface energy balance modeling (Narasimhan, 2008).

Goroshi et al. (2017) brought out inter-seasonal and inter-annual variability over India through trend analysis of monthly ET data generated by Zhang et al. (2010) using only 24 years' of NOAA monthly NDVI data (GIIMS : Global Inventory modelling and Mapping Studies) computed from AVHRR observations in optical remote sensing. The ET data were reported to be validated with 48 lysimeter stations of India Meteorological Department though monthly plots were shown for six stations only. The study has certain lacunae which are following: (i) thermal remote sensing has been found to be superior than optical remote sensing to estimate ET (Anderson et al., 2012**)**. Their study did not use any thermal remote sensing data. (ii) The study did not make use of a complete climate series of 30 years' satellite observations. (iii) IMD's lysimeter stations are reported to be 40 (32 gravimetric and 8 volumetric types) with lot of data discontinuity (IMD, personal communication). It was not clear how data gaps have been fulfilled; (iv) Several factors such as differences in height, growth and density of vegetation between the lysimeter and outside vegetation, interruption of deep percolation and horizontal flow components in soil within lysimeter tank, heat flux distortion caused by highly conducive steel walls, heavy rusting and corrosion in tanks due to exposure to soil, water and weather for long period of time can severely affect ET measurements (Farahani et al., 2007) using lysimeters. On the other hand, the tower-based ET flux measurements represent larger foot-print through surface energy balance measurements based on micro-meteorological principles depending on the fetch ratios. The above study did not try to use any such micrometeorological measurements available over India. (v) The above study did not involve any new modelling approaches within surface energy balance framework with respect to net radiation, soil heat flux, evaporative fraction specific to Indian sub-tropics. (vi) Though it showed ET variability and trend over major land cover types, inter-play of natural and anthropogenic influences on ET as well as ET trend explicitly over irrigated cropland were not highlighted. Even model simulated soil moisture data were used instead of climatic series of satellite-based (ESA scatterometers) surface soil moisture data. (vii) All these resulted into large validation error of 38% on seasonal and 17% on annual scale with respect to lysimeter stations. No bias correction was made on satellite-based estimates before showing mean from long-term satellite-based ET estimates. (viii) Moreover, the study did not bring out the trend in volume of water consumption pattern in different cover types.

Space Applications Centre of Indian Space Research Organization (ISRO) established a network of 23 micrometeorological towers of 10 m height during the years 2008 to 2011 with on-field data transmission facility through Yagi antenna to INSAT Data Relay Transponder (DRT) and subsequent reception at an earth station (Bhattacharya et al., 2009; Singh et al., 2014; Eswar et al., 2013).These towers have multi-height sensors for recording air temperature, relative humidity and wind speed and direction, four-component net radiation, two-depth soil heat flux and three-depth soil temperature, rainfall with a sampling frequency of 5 min and averaged over 30 min. These towers were located over cropland, grassland, shrubland and young forest spread over northern, southern, eastern, western and central parts of India including north-eastern hill region, Thar Desert and Andaman and Nicobar Islands with a fetch ratio varying from 1:50 to 1:100.

The surface energy balance data from these towers provided unique opportunity to characterize ET behavior and develop scaling functions (Bhattacharya et al., 2013) for net longwave radiation, bias correction of incoming shortwave radiation flux, soil heat fluxes with respect to satellite-based thermal remote sensing data. In the present study, these in conjunction with long-term satellite thermal remote sensing data enabled to estimate evapotranspiration at 0.08 grid resolution through simplified model of surface energy balance whose accuracy has already been evaluated through separate studies (Mallick et al., 2009). The country scale ET data at 0.08° grid resolution were generated through a combination of micro-metrological measurements, scaling functions, optical and thermal remote sensing observations from NOAA series of satellites during 1981 to 2000 and bias-corrected MODIS ET product for the period 2001 to 2010 to complete a climatic series of 30 years. The objectives of the present study are (i) to characterize baseline annual climatic ET over Indian sub-tropical vegetation; (ii) to evaluate the volumetric annual water consumption rates over major land cover types in the sub-tropics over three decades with special emphasis on irrigated cropland in the last decade; and (iii) to assess long-term ET trend to detect change hot-spots and regions of influence of natural and anthropogenic forcing factors.

2. Study Area

Climatic conditions of India are marked by tropical rainy season in its southern and temperate in the northern part. It is home to an extraordinary variety of climatic regions, ranging from tropical in the south to temperate and alpine in the north towards Himalaya where elevated regions receive sustained winter snowfall. The nation's climate is strongly influenced by the Himalayas and the Thar Desert. Strong temperature variations in different seasons and south-west monsoon are one of the most important characteristic of Indian climate. Variability in the onset, withdrawal and quantum of rainfall during the monsoon season has also profound impacts on water resources, power generation, agriculture, economics and ecosystems in the country. Temperature ranges from about 10 °C in winter to about 32 °C in summer season (Attri and Tyagi, 2010). For this study, the Indian landmass extending from 5 to 38" N and 68 to 100" E has been considered as shown in **(**Fig. 1).

3. Data used

3.1. Satellite-based evapotranspiration (ET)

3.1.1. ET from NOAA-AVHRR for 1981-2000

Monthly ET was estimated at 0.08° spatial resolution in terms of latent heat flux as a residual of single-source energy balance approach. Here evaporative fraction and net surface available energy (Mallick et al., 2009) determined from optical and thermal remote sensing data in terms of NOAA Pathfinder AVHRR Land (PAL) data were used. The cloud-gaps were filled through harmonic analysis of land surface variables such as NDVI, Surface albedo and Land surface temprature (LST). It also used bias-corrected shortwave radiation flux reanalysis field and linear and nonlinear scaling functions (Bhattacharya et al., 2013) for net long wave radiation and soil heat fluxes.

3.1.2. MODIS ET data for 2001–2010

The MODIS ET Product commonly known as MOD 16 ET Product

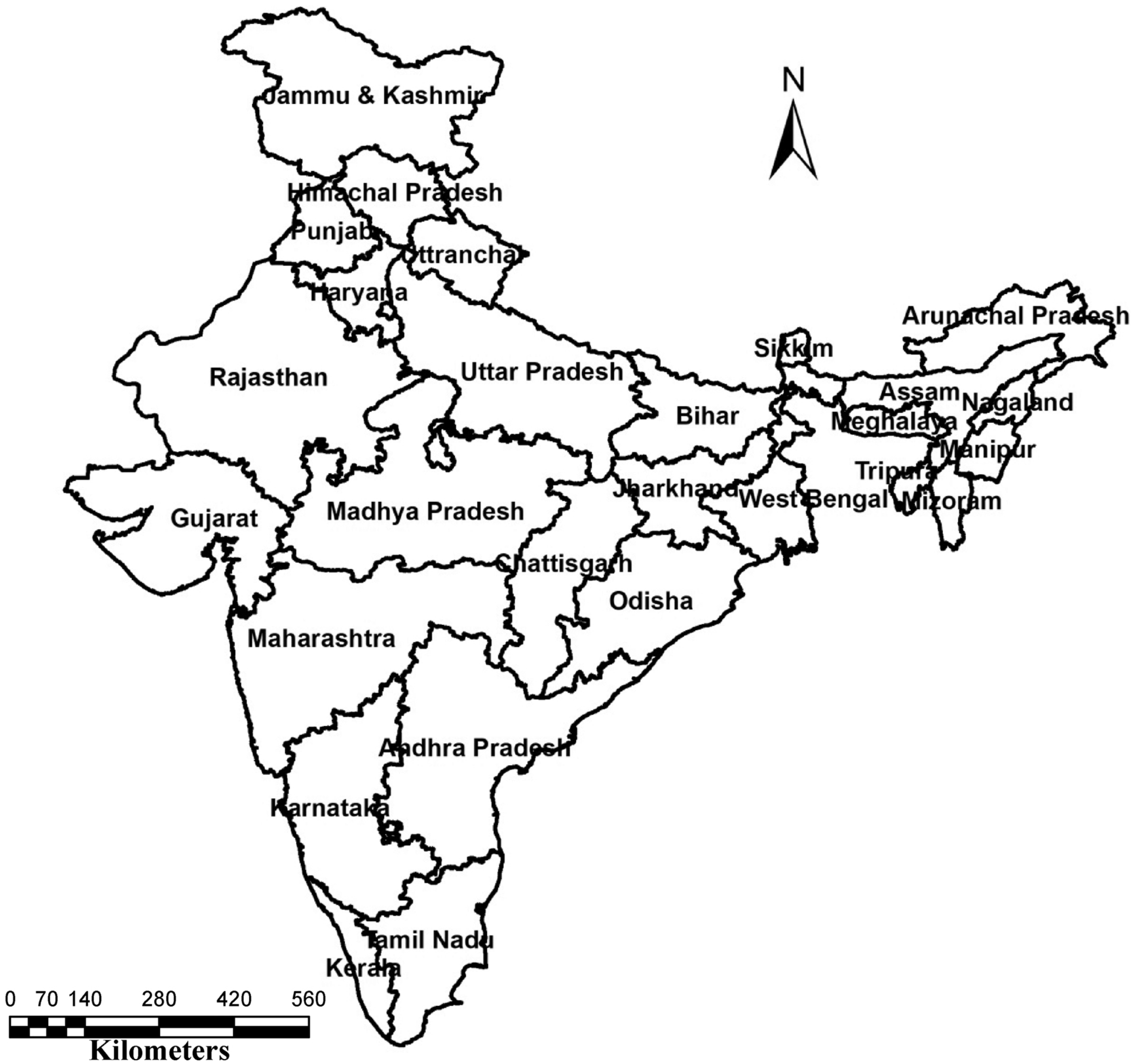

Fig. 1. Study area.

was used here having temporal resolution of eight days and spatial resolution of 1 Km. The detail description of MODIS ET generation is mentioned by (Mu et al., 2007and 2011) and (Cleugh et al., 2007) study. Annual ET, over Indian landmass for the period of 2001–2010 were generated through eight day ET Product. This annual ET was further resampled to 0.08° grid resolution before using in this study.

3.2. Gridded rainfall

The daily measured rainfall records, converted into gridded rainfall at 0.5° x 0.5° grid resolution, were used for this study. The gridded data were generated by (Rajeevan et al., 2006) using Shepard interpolation method, where measured rainfall data were from 1803 rain gauge stations of India Meteorological Department (IMD). The daily gridded rainfall data were further summed up to compute annual rainfall. These gridded daily rainfall data were averaged for the period of 1981–2010.

3.3. Satellite-based surface soil moisture (SSM) data

The global product of daily volumetric surface (0–5 cm) soil moisture (SSM) at 25 km spatial resolution has been used here for the period of 1981–2010.This is a merged product from the observations of series of ESA scatterometers and *in situ* moisture measurements of global soil moisture data bank (http://climate.envsci.rutgers.edu/soilmoisture).The data were obtained from ESA (http://www.esa-sm-cci.org/).The annual mean SSM of ESA was computed from daily soil moisture data over Indian landmass during the above mentioned period.

3.4. Reanalysis data

The reanalysis data field from MERRA 2D on surface incident shortwave flux (SWF) was used for the current study. The spatial resolution of MERRA 2D is 2/3° (longitude) x 1/2° (latitude). The monthly incoming shortwave radiation data were converted to annual scale for the period of 1981 to 2010.

4. Land use Land cover map of India

The land use land cover (LULC) maps of India at 100 m spatial resolution, produced through International Geosphere Biosphere Programme (IGBP) for 1985, 1995 and 2005 (https://daac.ornl.gov/), were used for three decades, 1981–1990, 1991–2000 and 2001–2010, respectively. Details of the product are given in Meiyappan et al. (2017)

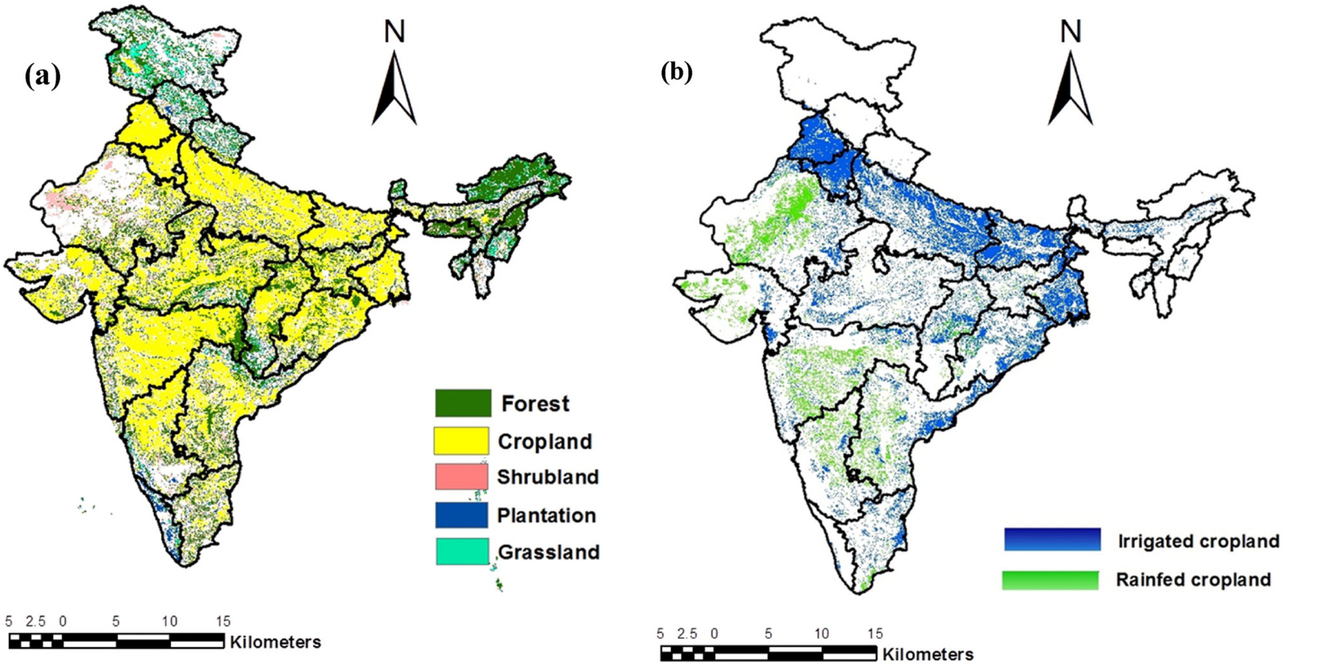

Fig. 2. Distribution of (a) major land cover types, (b) irrigated and rainfed cropland.

and Roy et al. (2016). These were resampled to 0.08° grid resolution. Out of 19 classes, five broad vegetation classes (Fig. 2a) of cropland, forest (including all its sub-types), shrubland, grassland and plantation were used for trend analysis. However, IGBP LULC does not contain classes for irrigated and rainfed cropland. Therefore, the LULC derived from SPOT-VGT data (Agrawal et al., 2003) at 1 km spatial resolution containing irrigated and rainfed cropland classes (Fig. 2b) has been used for the analysis for the period 2000–2010 for the comparison of NOAA and MODIS ET as well as ET trend analysis over irrigated cropland and its comparison with respect to rainfed cropland, grassland and forestland. SPOT-VGT-based LULC was resampled to 0.08° grid resolution.

5. Methodology

5.1. Regional land-ET model

Actual evapo-transpiration (AET) (here after referred as ET) was estimated from latent heat fluxes (λE *or* LE) and latent heat (L) of evaporation (Brutsaert and Chen, 1996). Latent heat flux (λE) is generally computed as a residual of surface energy balance (Kustas et al., 1994; Moran et al., 1994; Mallick et al., 2007). A single (soil-vegetation complex as single unit) source surface energy balance can be written as,

$$Rn = H + G + \lambda E + M \tag{1}$$

The energy component for metabolic activities(M)isverysmall (Samson and Lemeur, 2001) and hence can be neglected. The Eq. (1) can be rewritten as,

$$\lambda E = Rn{-}G{-}H \tag{2}$$

R_n = net radiation (Wm^{-2}), H = sensible heat flux (Wm^{-2}), G ground heat flux (Wm^{-2}),

R_{n-} G = net available energy (Q) in Wm^{-2}.

Assuming energy balance closure at any instance during a day Eq. (2) can be written as-

$$\lambda E = Q.\ \Lambda = (Rn{-}G).\ \Lambda \tag{3}$$

The Λ_{noon} was estimated at regional-scale from two-dimensional scatter of noontime LST and albedo (Roerink et al., 2000 and Verstraeten et al., 2005) using NOAA PAL ten-day.

In the present study, noon-time evaporative fraction (Λ_{noon}) was determined from noon-time LST and albedo. This was used as daily equivalent (Λ_{24}) based on the findings of Mallick et al. (2009) regarding invariant evaporative fraction during major portion of daytime hours which largely ifluence daily average latent heat fluxes or evapotranspiration. The formulation of evaporative fraction from LST – albedo 2D scatter is given as :

$$\Lambda_{noon} = \frac{LE}{H + LE} \approx \frac{T_H - T_s}{T_H - T_{\lambda E}} \tag{4}$$

Here, T_H is maximum LST ($= T_s$) on dry edge i.e. radiation control branch computed as a linear function of surface albedo. $T_{\lambda E}$ is the minimum T_s on wet edge or evaporation control branch computed as a linear function of surface albedo.

5.2. Adaptation with NOAA PAL, reanalysis data and scaling functions

Monthly mean evaporative fraction was obtained from temporally smoothened ten-day or eight-day time-composites of noontime LST and albedo. Temporaly smoothning of noontime LST has been carried out using HANTS algorithm (Roerink et al., 2000; Zhou et al., 2015). NOAA PAL three 10 day evaporative fraction data in a given region were used to compute mean monthly evaporative fraction.

Net radiation ($\boldsymbol{Rn_d}$) is composed of net shortwave ($\boldsymbol{Rns_d}$) and net longwave ($\boldsymbol{Rnl_d}$) components. Daytime net shortwave radiation was computed from monthly bias-corrected reanalysis monthly surface insolation data from MEERA 2D and satellite-based monthly surface albedo. The bias correction model was developed from AMS measurements during 2011. The monthly mean albedo were computed from days time composite albedo. For NOAA PAL, three composites were used to compute monthly average.

Surface daytime net longwave radiation generally requires day time monthly mean of LST, air temperature and precise determination of surface emissivity and air emissivity. The day time mean of LST is possible if all-sky (clear and cloudy-skyboth) LST is available diurnally. NOAA AVHRR provides single noon-time LST per day. Therefore, daytime net longwave radiation (Rn_{ld})was determined as a function of net shortwave radiation (Iziomon et al., 2000and Bhattacharya et al., 2013). The coefficient ‘a’ and ‘b’were found to vary from -0.124 to

Table 1
Comparision of annual ET from MODIS with respect to AMS.

Station name	Latitude	Longitude	Annual-ET(AMS) (mm)	Annual ET-MODIS (mm)
Nawagam	22° 47'	72° 34'	936	645
Bharatpur	27 ° 12'	77 ° 27'	926	513
Hosangabbad	22 ° 41'	77° 44'	692	644
Crida	17° 34'	78 ° 59'	590	666
BCKV	23° 05'	88 ° 54'	805	814
Junagad	21° 29'	70° 26'	637	578
LPSC	81° 7'	77° 33'	1105	1473
Kanha	22° 21'	80° 34'	494	458
Mean			773	723

-0.245 and -0.243 to 16.25, respectively for different seasons (Bhattacharya et al., 2013).

$R_{nld=} \alpha * R_{nsd} + b$

Soil heat flux depends on soil temperature gradient and soil thermal conductivity, which are hard to determine using thermal remote sensing data. However, the fraction of soilheat flux to net radiation varies from 0.1 to 0.3 from well vegetated land to bare soil conditions. A host of empirical soil heat flux models (Sun et al., 2013) are available using LST, albedo, NDVI developed elsewhere. In the present study, empirical logarithmic function (Y = -12.5*Log_e(X)- 1.317 ; Y = monthly ratio of soil heat flux and net radiation ; X = monthly NDVI) was developed between ratio of monthly average of day time soil heat flux and net radiation monthly 1-Km resolution NDVI data from(Bhattacharya et al., 2013) having NOAA PAL eqivalent spatial resolutions. Thus, the monthly mean net available energy and monthly evaporative fraction were used to estimate regional day time monthly mean latent heat fluxes, regional monthly mean and annual ET loss.

5.3. ET modellling approach using MODIS data

The MOD16 global ET product (Mu et al., 2011) at 1 Km spatial resolution, provided by Earth Observing System of the National Aeronautics and Space Administration (NASA/EOS) as part of global ET project (http://www.ntsg.umt.edu/project/mod16) were used in the present study. For this, ET data from MODIS AQUA for the years 2001 to 2010 were used. The MOD16 ET product was based on the Penman-Monteith formulation (Monteith, 1965) that used MODIS biophysical and geophysical products such as

(i) Global collection 4 land cover type 2 (MOD12Q1), (Friedl et al., 2002)
(ii) Collection 5FPAR/LAI (MOD15A2) (Myneni et al., 2002)
(iii) Collection 5 MCD43B2 and MCD43B3 albedo (Liang et al., 2003and Lucht et al., 2000)
(iv) Collection 4 land cover types and NASA's MERRA GMAO daily meteorological reanalysis fields at 2/3° x 1/2° grid resolution. Though the MOD16 algorithm (Mu et al., 2011) is an improved version of a previous version (Mu et al., 2007), it does not use any thermal remote sensing data for solving energy balance, the improvement made in (Mu et al., 2007) by (Mu et al., 2011) is as follows.

The improvements included: 1) simplification of the calculation of vegetation cover fraction, 2) calculation of ET as the sum of daytime and nighttime components and soil heat fluxes, 4) improvement in the methods to estimate stomatal conductance, aerodynamic resistance and boundary layer resistance; 5) separation of dry canopy surface from the wet and hence canopy water loss includes evaporation from the wet canopy surface and transpiration from the dry surface and 6) division of soil surface into saturated wet surface and moisture surface. Soil evaporation includes potential evaporation from the saturated wet surface

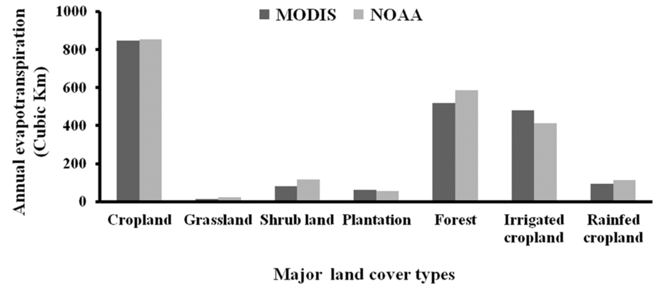

Fig. 3. Comparaison of annual ET from NOAA and MODIS over major land cover types for a common year 2000.

and actual evaporation from the moist surface. The annual MODIS ET for the period of year 2000 to 2010 over Indian landmass at 1 Km spatial resolution were resampled to 0.08° grid resolution and were subsequently used in this study.

5.4. Generation of regional trend statistics

The rank-based (Mann, 1945 and Kendall, 1975) method is a non-parametric approach to assess the significance of monotonic trends in hydro-meteorological time series (Burn and Hesch, 2007). Parametric methods require the data to be independent and normally distributed. But, for smaller departures from normality, non-parametric methods are sometimes better than parametric methods (Hirsch et al., 1991).

In the present study, one of the most widely used non-parametric (Mann-Kendall tests) methods was applied with time series data of annual ET, rainfall, annual mean of SSM and surface insolation for the recent decade (2001–2010) to find out trend significance over major land cover types in the Indian sub-tropics.

Let x_1, x_2, x_3 represent n data points where xj represents the data point at time j. Then the Mann-Kendall statistic (S) is given by,

$$S = \sum_{k=1}^{n=1} \sum_{j=k+1}^{n} \mathrm{Sign}(X_j - X_k)$$

Where,

$\mathrm{Sign}\,(X_j - X_k) = 1 \text{ if } (X_j - X_k) > 0$

$= 0 \text{ if } (X_j - X_k) = 0$

$= -1 \text{ if } (X_j - X_k) < 0$

A very high positive value of S is an indicator of an increasing trend; very low negative value indicates a decreasing trend. Then variance of S, VAR(S) was calculated by the following equation.

$$\mathrm{VAR}(S) = \frac{1}{18}[n(n-1)(2n+5) - \sum t_P(t_P+1)(2t_{P+}5)] \quad (5)$$

Where n is the number of data points, g is the number of tied groups (a tied group is a set of sample data having the same value), and t_p is the number of data points in the p^{th} group. Then a Z-statistic was computed as follows:

$$Z = S - \frac{1}{[\mathrm{VAR}(S)]^{\frac{1}{2}}} \text{ if } S > 0 \quad (6)$$

$$= 0 \text{ if } S = 0 \quad (7)$$

$$= S + \frac{1}{[VAR(S)]^{\frac{1}{2}}} \text{ if } S < 0 \quad (8)$$

Here, Mann-Kendall tests are used to demonstrate any presence of possible trends against the null hypothesis of having no trends. Where the tabulated and calculated Z-statistics were compared at 95% and 90% (p = 0.05, p = 0.1) level of significances. The trend is said to be significantly decreasing if sample Z is negative and absolute Z is greater

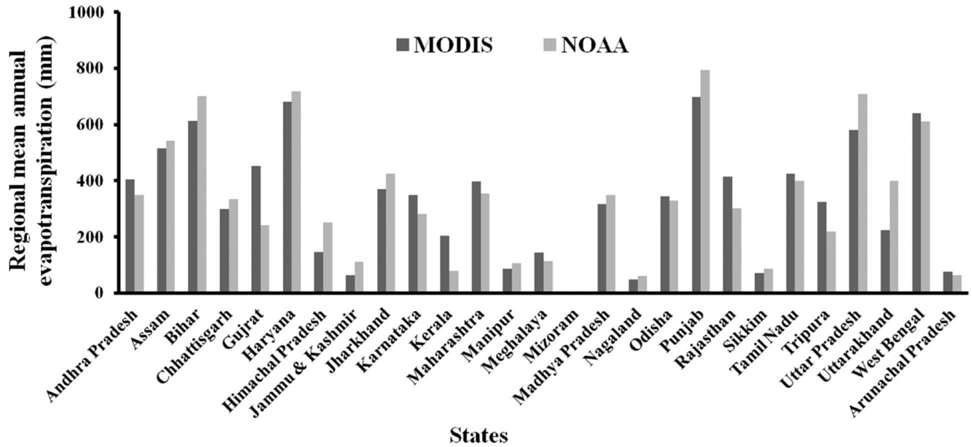

Fig. 4. Comparison of regional mean annual ET over NOAA and MODIS over cropland in different Indian States for a common year 2000.

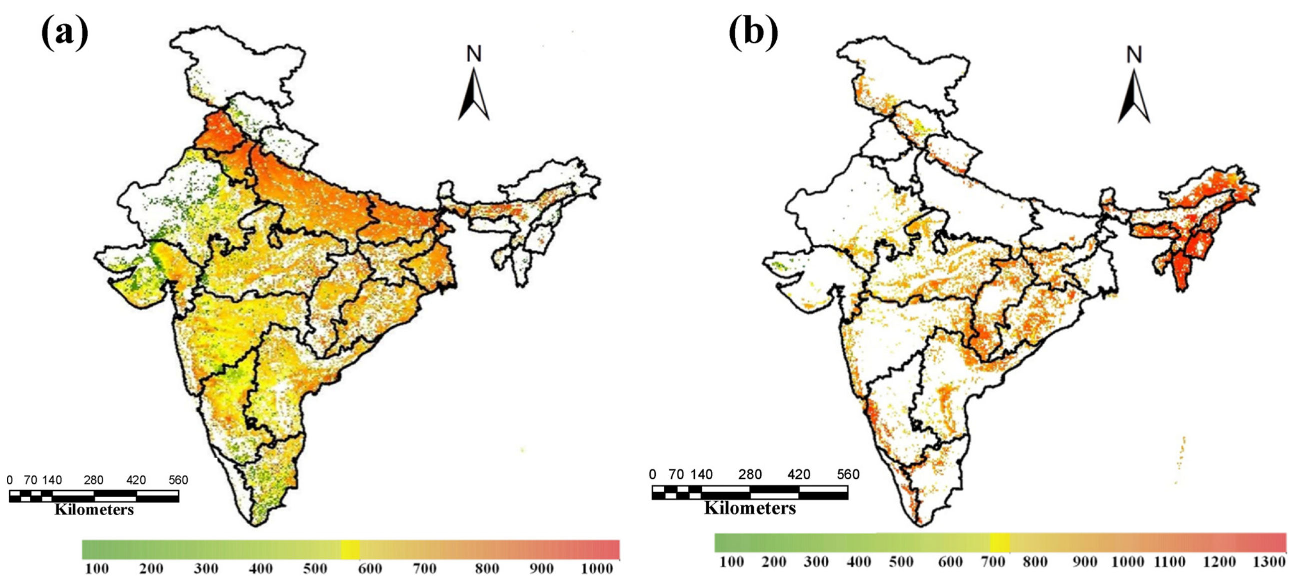

Fig. 5. Spatial distribution of annual baseline climatic ET (mm) over (a) cropland and (b) forest.

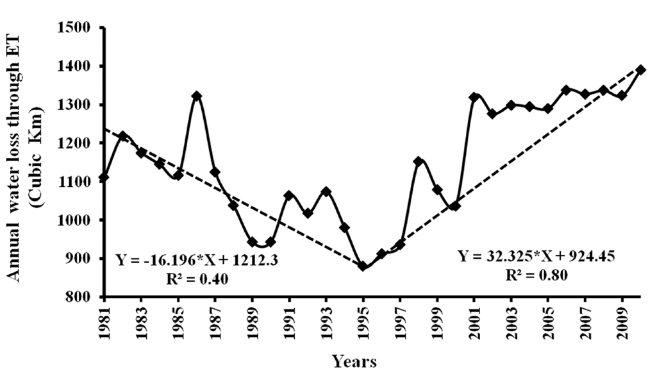

Fig. 6. Climatic variability of annual ET for the period 1981–2010 over Indian sub-tropical vegetation.

than the tabulated value at a given level of significance. The trend is said to be increasing significant if the sample Z is positive and is greater than the level of significance. If the computed Z is less than the level of significance, the trend is not significant.

6. Results and discussion

6.1. Inter-comparison of annual ET from NOAA and MODIS

The generated climatology of the present work is a combination of 30 years' ET (1981–2010) where, the initial 20 years (1981–2000 ET) was derived from NOAA PAL data (based on LST-albedo evaporative fraction and surface energy balance), and the last 10 years (2001–2010 ET) was of MODIS (based on P-M approach).

The NOAA-PAL ET has been generated taking into account single-source energy balance approach (Mallick et al., 2009) which was validated with micrometeorological measurements of LASPEX (Land Surface Processes Experiment) over Anand region of Gujarat, India for noontime and daytime. The RMSE of latent heat flux over LASPEX sites was found to be 22% of measured mean for noon time and 15% of measured mean for day-time average with correlation coefficients (r) of 0.66 and 0.82, respectively between NOAA estimates and micro-meteorological measurements.

The annual MODIS ET for the year 2010 was compared with ET computed from in-situ micro-meteorological measurements from India for eight different AMS (Agro-met station) locations (Table 1). The annual MODIS ET showed RMSE of 0.29 mm d^{-1} and a mean bias of -6.4% with correlation coefficient of 0.68. MODIS ET was found to have lower values when compared to those derived from majority of AMS

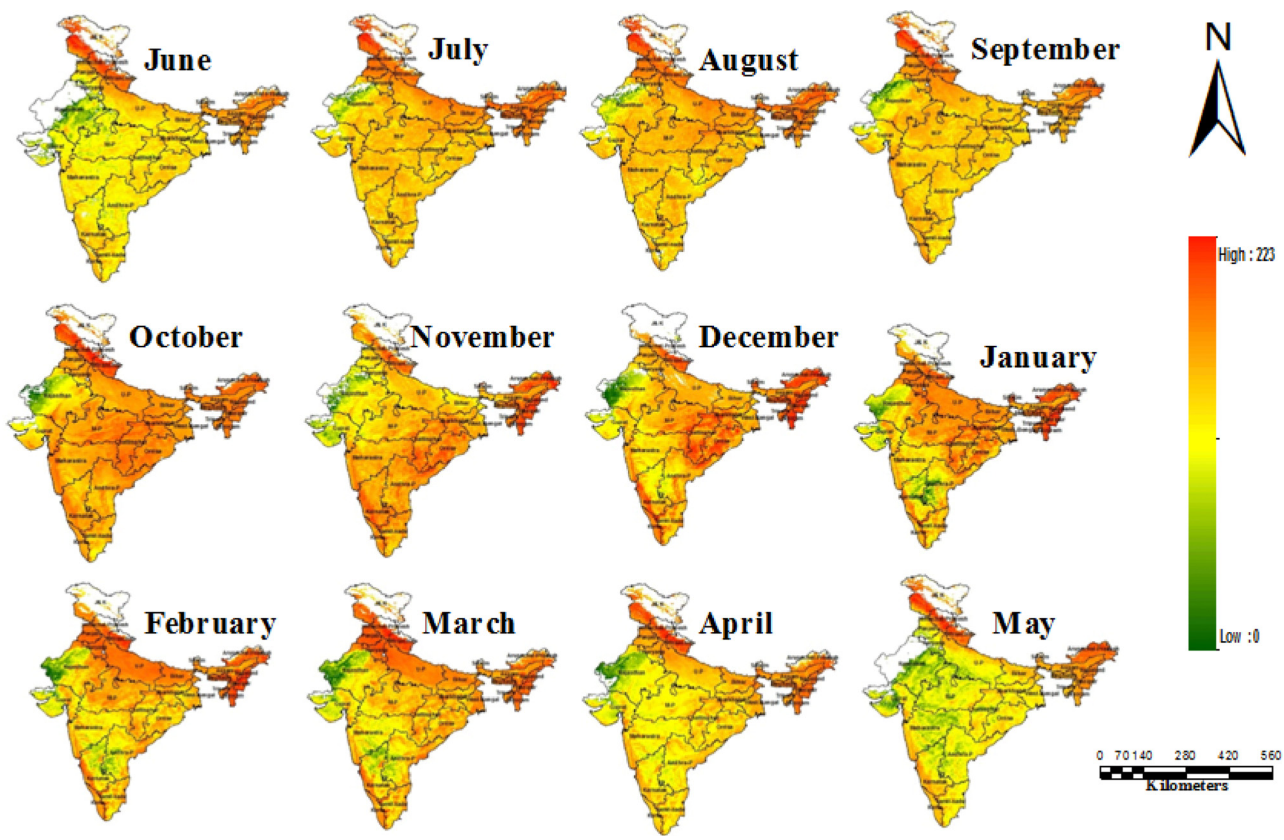

Fig. 7. Monthly climatic ET (mm) over Indian vegetated surface.

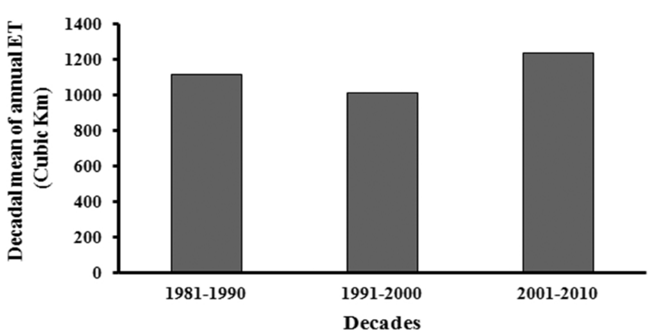

Fig. 8. Decadal trend of annual water loss through evapotranspiration over. Indian vegetation.

stations. The footprint mismatch of MODIS observations and AMS measurements is one of the major sources of underestimates. In agricultural systems, advection from surrounding fields influence turbulent heat fluxes such as sensible and latent heat fluxes within surface layer of Atmospheric Boundary Layer (ABL). These might influence the Bowen ratio and evapotranspiration estimation through micrometeorological measurements in current Agro-Met Stations (AMS). The MODIS ET algorithm does not correct for micro-advection. This difference might also lead to the deviation between MODIS and AMS ET.

The annual ET from NOAA PAL was compared with annual MODIS ET for an overlapping year of 2000 over different land cover types (Fig. 3) and states of India (Fig. 4). Before comparison, MODIS and NOAA ET estimates were corrected for bias for cropland obtained through in situ measurements with respect to AMS and LASPEX experiments as reported above. The correlation cofficient over land cover types and Indian states were 0.98 and 0.93, respectively. The mean deviation of MODIS ET as compared to NOAA PAL ET was found to be −7.3% across different cover types and -1.5% over across different

Table 2
Trend of annual consumptive water use over different LULC and Man-Kendall test statistics for three decades during.1981–2010.

LULC	S-Score	Z-Score	TS
1981-1990			
Agriculture	11.18	−2.41	Y(−)
Forest	−18	−1.52	Y(−)
Grassland	10	0.80	Y(+)
Shrub	−27	−2.32	Y(−)
Plantation	−18	−1.52	Y(−)
1991-2000			
Agriculture	1	0	No
Forest	−3	−0.17	No
Grassland	−3	−0.17	No
Shrub	6	0.44	No
Plantation	3	0.17	No
2001-2010			
Agriculture	19	1.61	Y(+)
Forest	17	1.43	Y(+)
Grassland	−5	−0.35	No
Shrub	23	1.96	Y(+)
Plantation	0	0	No

S: Score, Z: Score, TS: Test of Significance, NA: Data Not available, Y (+): Significantly.

Indian states.

Irrigated cropland showed over estimates of ET from MODIS as compared to NOAA of the order 16.7% (Fig. 3) in the year 2000. In contrast, rainfed cropland showed underestimates in ET from MODIS as compared to NOAA of the order of 17.6%. In MODIS ET, no thermal remote sensing data were used. NOAA ET has been derived using thermal remote sensing. It has been reported that thermal remote sensing has higher sensitivity for ET estimation where surface temperature and albedo fluctuations were largely governed by irrigation water management irrespective of LAI development. In rainfed

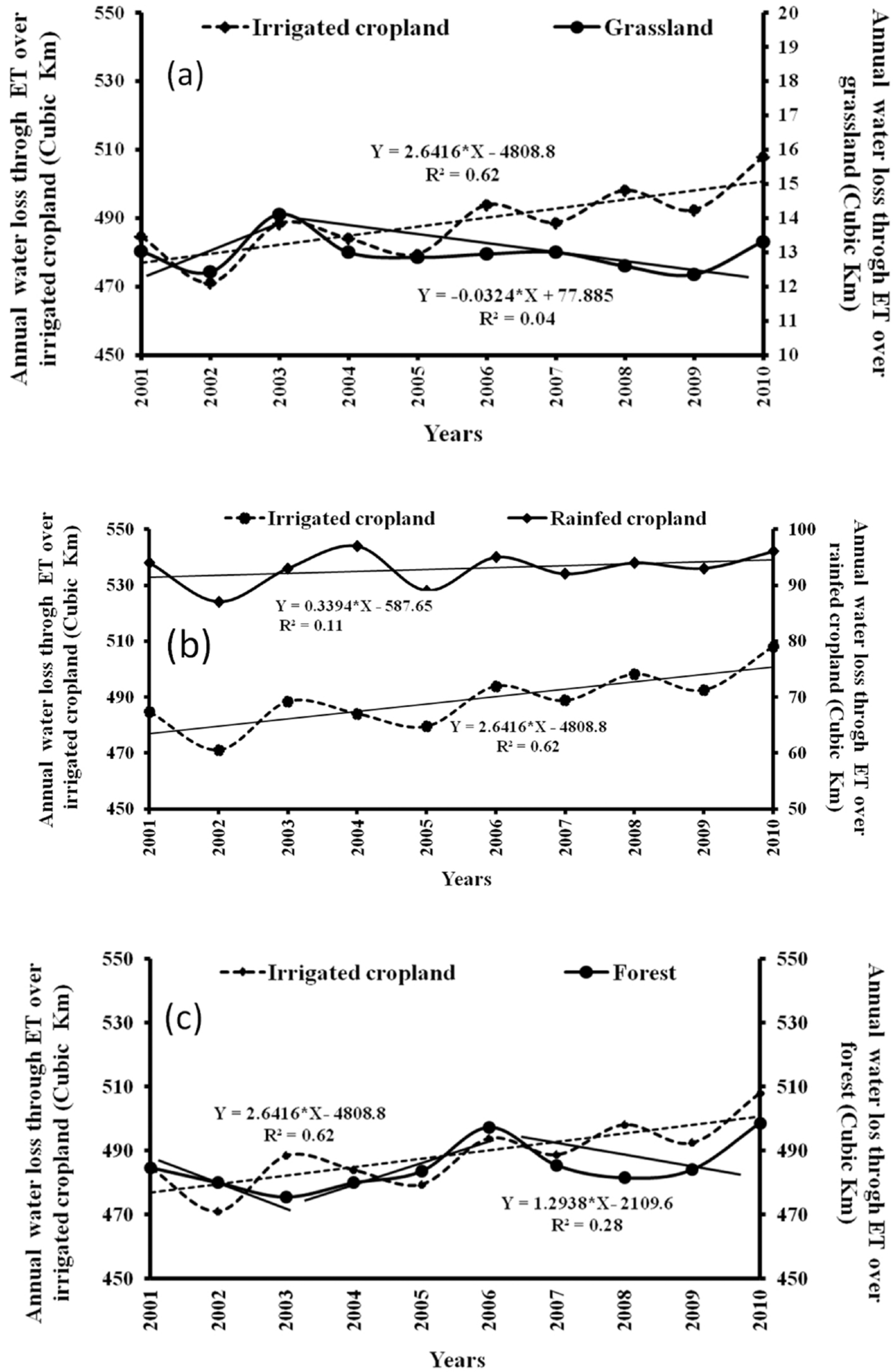

Fig. 9. Comparison of annual water consumption patterns over irrigated crop land, grass land and forest.

agriculture, water is ill-managed and ET variability largely follows LAI variability. These contrast in water supply and utilization situation might cause differences in responses to different ET estrimation approaches. This might bring similar but opposite differences between MODIS and NOAA ET in irrigated and rainfed croplands. However, there is little difference (< 1%), in general, between two sources of ET over cropland.

Since, there is a fair correlation and less negative percent deviation in annual ET data of MODIS with respect to NOAA ET data over different cover types and geographic regions, the ET data from MODIS for 2001–2010 was used seemlessly alongwith NOAA ET data for the period 1981–2000 to carry out time series analysis using IGBP LULC. However, the recent trend in ET over irrigated cropland was compared with ET trend over rainfed, grassland and forest using SPOT-VGT LULC for the period of 2001–2010.

6.2. Baseline climatic ET over Indian sub-tropical vegetation

The climatic mean of thirty (30) years' annual ET at 0.08° resolution showed a wide spatial variation from 100 to 1300 mm (depth of water) over Indian vegetated surface with cropland ET ranging from 100 to 1000 mm (Fig. 5a) and forest ET ranging from 500 to 1300 mm (Fig. 5b). The plot (Fig. 6) of year-to-year variation of annual ET from vegetated area of Indian sub-tropics showed a sharp declining trend during 1981 to 1995 with intermittent rise and fall. This could be associated with either rainfall or solar dimming. The solar dimming has

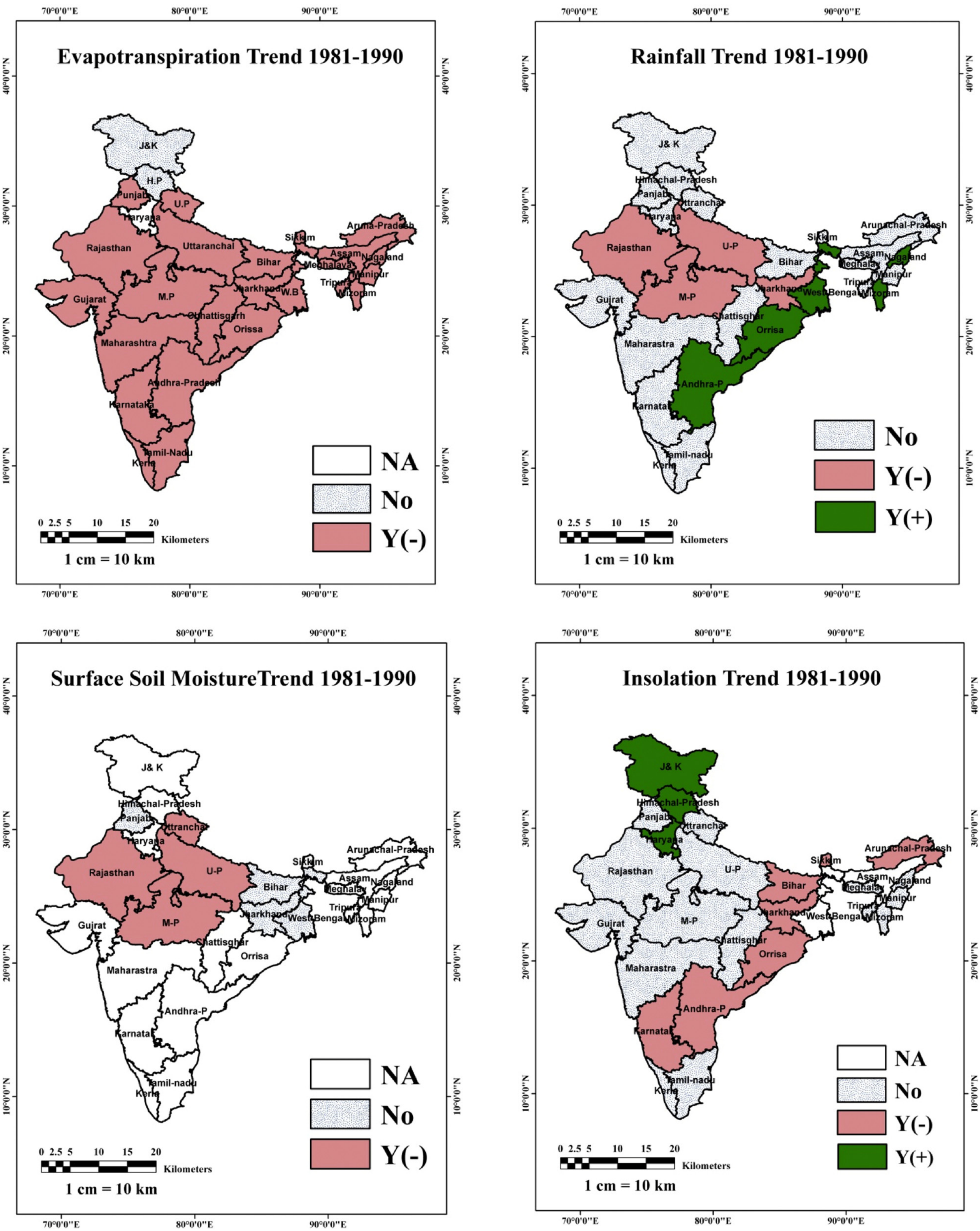

Fig. 10. Trend assessment of long-term ET and detection of change hot-spots.

been noticed over major parts of India owing to rise in aerosol load and cloudiness (Padma Kumari and Goswami, 2010). Decrease in ET was observed at the rate of -16 cubic km yr^{-1} till 1994, however, after 1995 an increasing trend in ET was observed with a rate of 34 cubic $kmyr^{-1}$. Further, the intermittent decline in ET was noticed coincident to intermittent drought years of 2000, 2002 and 2009. The overall ET trend contradicts the IPCC (Inter-Governmental Panel for Climate Change) climate change prediction (IPCC, 2000) of accelerated water cycle from model simulations due to global warming.

The spatial distribution of monthly climatic ET (Fig. 7) showed a large variation up to 223 mm yr^{-1}. Monthly ET generally increases from June with the onset of south-west monsoon rainfall, reaches a

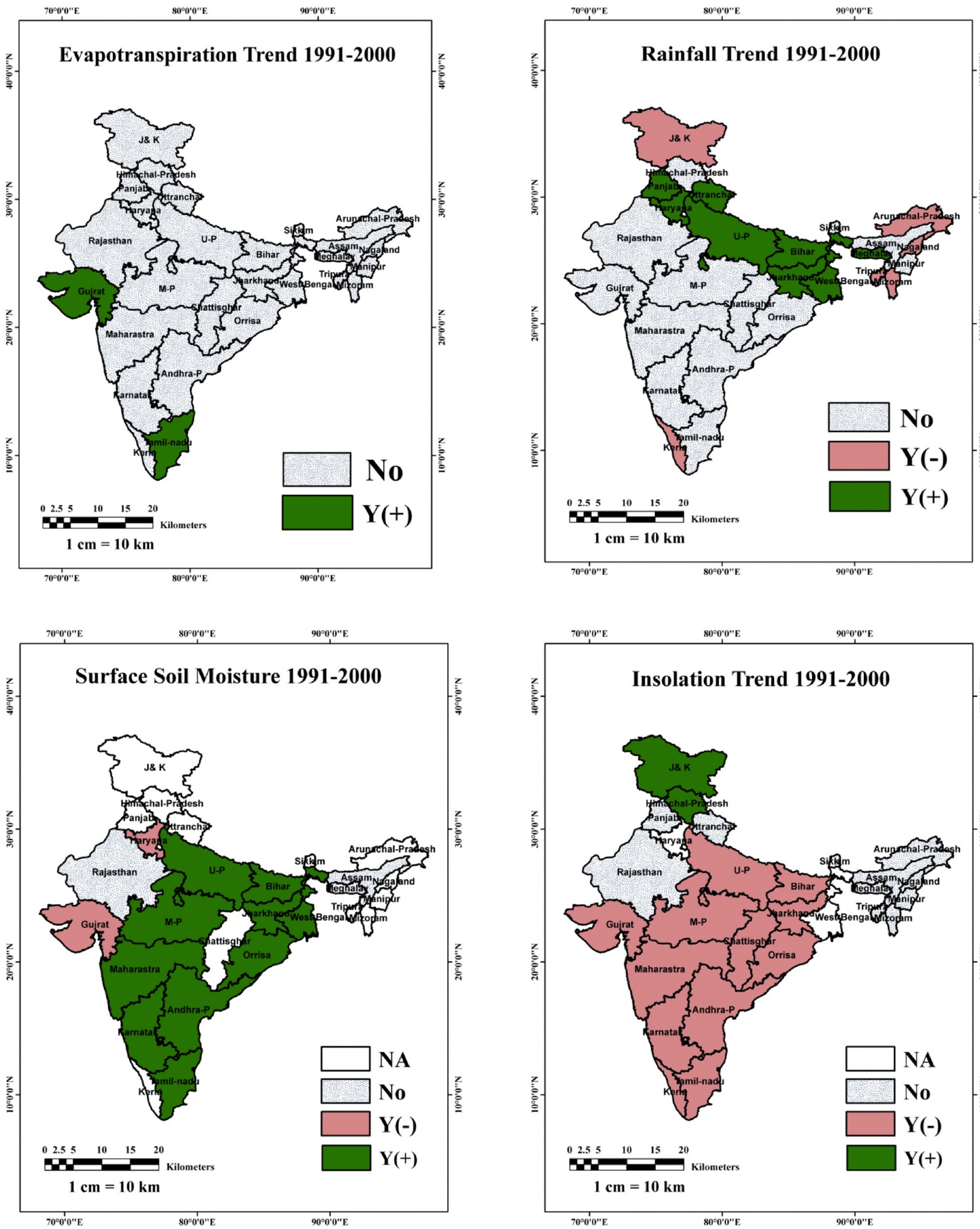

Fig. 10. (*continued*)

peak during September followed by a decline during October and November. Again, it starts increasing from December and peaks in March especially over Indo-Gangetic plain, south-east, southern plains and part of western plain where irrigation is practiced.

This showed that monthly ET dynamics could capture the impact of rainfall and irrigation in two consecutive growing seasons which start in June over Indian sub-tropics. The decadal (10 year) mean also showed a decline in ET over vegetated surface from 1114 Cubic Km during 1981–1990 to 1013 Cubic Km during 1991–2000 followed by an increase to 1236 Cubic Km during 2001–2010 (Fig. 8).

The synoptic and systematic ET data using time series observations from satellite platform seem to be influenced by the impacts of both

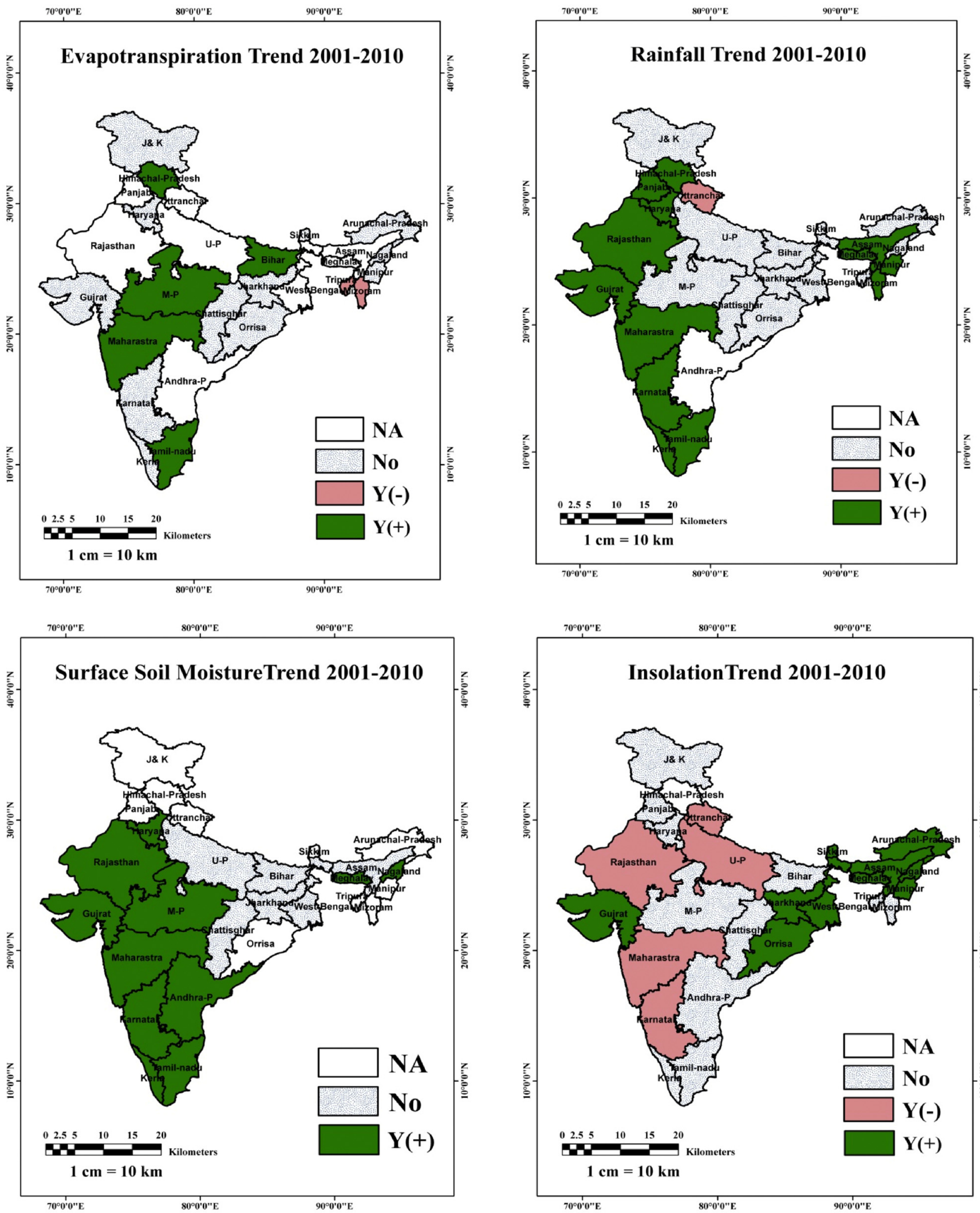

Fig. 10. (*continued*)

natural (e.g. rainfall, solar radiation, temperature etc.) and anthropogenic forcing factors (e,g. irrigation, change in pattern of cover types) over vegetated surface. But present state-of-art climate prediction models rarely incorporate any anthropogenic factors to project real-life impacts.

6.3. *Annual water consumption pattern by major land cover types of Indian sub-tropics*

The annual loss of water through ET is generally considered as consumptive water use by vegetative systems. The Man-Kendall trend statistics of annual water consumption patterns of major Indian land cover types during the years 1981–2010 are presented in (Table 2). The

Table 3
ET trend during 2001–2010 and Man-Kendall test statistics in different Indian States.

States 2001-10	Annual ET			Annual rain Fall			Annual mean SSM			Annual mean SWF		
	S	Z	TS	S	Z	TS	S	Z	TS	S	Z	TS
	Pre-dominantly Plain and Plateau Land											
Bihar	15	1.09	Y (+)	−1	0	No	1	0	No	8	0.626	No
Madhya Pradesh	24	1.8	Y (+)	1	0	No	27	2.3	Y (+)	−9	0.716	No
Maharashtra	15	1.1	Y (+)	13	1.8	Y (+)	17	1.4	Y (+)	−16	−1.3	Y (−)
Tamil Naidu	25	1.9	Y (+)	7	0.9	Y (+)	27	2.3	Y (+)	−6	−0.4	No
Pre- Dominantly Hilly Land												
Tripura	−29	−2.2	Y (−)	1	0	No	NA	NA	NA	6	0.447	No
Mizoram	−16	−1.2	Y (−)	13	1.8	Y (+)	NA	NA	NA	4	0.268	No
Himachal Pradesh	13	0.9	Y (+)	7	0.9	Y (+)	NA	NA	NA	−5	−0.3	No

S: Score, Z: Score, TS: Test of Significance, NA: Data Not available, Y (+): Significantly.

trends were significant and negative for 1981–1990 over cropland, forest and shrubland followed by no trend in 1991–2000 and positive trend during 2001–2010. The Z-scores were found to range from −1.52 to −2.41 and 1.43 to 1.96 during 1981–1990 and 2001 to 2010, respectively over the above land cover types. Positive and negative trends were found for grassland and plantation, respectively during 1981–1990 followed by no trends during 1991–2000 and 2001–2010. The annual water consumption, averaged over this period, from Indian cropland was found to be the highest 890 Cubic Km followed by the Indian forest ecosystem (575 Cubic Km).

Annual water consumption trend over irrigated cropland is shown in Fig. 9 and it was compared with other rainfed vegetative systems such as grassland, rainfed cropland and forest as shown in Fig. 9a, b and c. Significant positive consumption trend is noticed in irrigated cropland with R^2 = 0.62 between 470 and 510 Cubic Km with an average rate of increase of 4 Cubic Km yr^{-1}. This might be due to increase in cropping intensity, better crop management practices and change in cropping patterns (Milesi et al., 2010) such as multiple cropping in a year (Raghuvanshi, 1995) instead of mono-crop and cultivation of horticulture cash crops instead of field crops. Change in irrigation sources (Gandhi and Namboodiri, 2009; Suhag, 2016) contributing more towards productivity of agricultural field can also be a cause of increasing water consumption in irrigated land. Rainfed cropland did not show any significant trend in water consumption pattern.

On the other hand, steady decline in water consumption trend is noticed for grassland and forest after 2003 and 2006, respectively with average rates of 0.3 Cubic Km yr^{-1} and 3.7 Cubic Km yr^{-1}, respectively. Crossover points were noticed between water consumption trend over irrigated cropland and grassland, and between irrigated cropland and forest during 2005 and 2007, respectively. This might be due to increasing water consumption over irrigated croplands surrounding forest watershed at the cost of water yield from grassland and forest watersheds.

6.4. Decadal ET trend in relation to forcing variables

Decadal trends of annual ET within 30 years' period over different Indian states and its natural forcing factors such as rainfall and surface insolation (incident radiation flux) or incident Shortwave Radiation Flux (SWF) alongwith trend in Surface Soil Moisture (SSM) have been depicted in Fig. 10. It may be mentioned that surface moisture variability occurs due to rainfall variability as well as man-made changes (so-called anthropogenic forcings) in water allocation and application patterns through new canal command area, ground-water pumping, tank-based and sprinkler-drip irrigation etc. During 1981–1990, significant negative trend in ET was observed over majority region covering 89% of Indian states. This can be attributed to significant reduction in annual rainfall, insolation, surface soil moisture over south-eastern, eastern, part of central and western India. There was significant increase in annual rainfall over north-western India. However, the increase could not trigger the increase in ET by offsetting the solar dimming effect in this region. During 1991–2000, largely no trend in annual ET was noticed over majority (89%) of Indian states. Significant increase in annual rainfall over Indo-Gangetic Plain and surface soil moisture over rest part of India were noticed while solar dimming prevailed during period over majority of Indian landmass. Both positive and negative forcings balanced each other to result into largely no trend in annual ET. But in the recent and last decade (2001–2010), significant increase in annual ET was noticed over 29% of the Indian States with largely no trend over rest of India. The trend analysis of ET with respect to forcing variables in the recent decade is described below. A summary of significant ET trend during 2001–2010 and Man-Kendall test statistics in different Indian states is given in Table 3.

The plain and plateau lands comprising states such as Bihar, Madhya Pradesh, Maharashtra, Tamil Nadu showed significantly increasing ET trend. Among pre-dominantly hilly states, two north-eastern states such as Tripura and Mizoram showed significantly decreasing annual ET trends. However, northern hill state such as Himachal Pradesh showed significantly increasing ET. Among the four arable states, two states such as Maharashtra and Tamil Nadu showed significantly increasing ET (with S 15 and 25, and with Z 1.1 and 1.9, respectively) along with significant increase in annual rainfall (S = 13 and 7, Z = 1.8 and 0.9) and SSM (S = 17 and 27, Z = 1.4 and 2.3). Though significantly increased ET trend was observed in other two states such as Bihar (S = 15, Z = 1.09) and Madhya Pradesh (S = 24, Z = 1.8) no significant trend in rainfall was observed for both of these states. However, significant increase in SSM (S = 27, Z = 2.3) was noticed in Madhya Pradesh (M.P hereafter) but not in Bihar.

Increasing ET trend for the two states, M.P and Bihar, without being impacted by natural forcing might be attributed due to developments in agricultural practices such as increase in irrigated area under canal command, increased frequency and amount of irrigation, increased ground water pumping, increase in cropping intensity and change in cultivars (Gholkar et al., 2014). But these contrasting situations need thorough investigation at finer scales with more statistics on crops, irrigation and intensification. In contrast, there was significant increase in annual ET (S = 13, Z = .09) over northern hilly state such as Himachal Pradesh along with significant increase in annual rainfall (S = 7, Z = 0.9).There were no significant trends in surface insolation also in all the three states indicating that there was no possibility that increased cloud cover is reducing ET (Fig. 11).

The major possible factor of decreasing ET (S = -16 and -29, Z = -2.2 and -1.2) under increasing rainfall in these two north-eastern hilly states could be due to shifting cultivation, which is still practiced in some north-eastern states leading to significant change in land cover (Anonymous, 1999). As mentioned by Silva et al. (2011) that due to Jhum cultivation not only soil quality but productivity of cereals crops and vegetables may also decrease in spite of increasing rainfall along with emission of such gases CO_2, CH_4, CO, N_2O, and NO_X which contribute for changing climatic condition of this area.

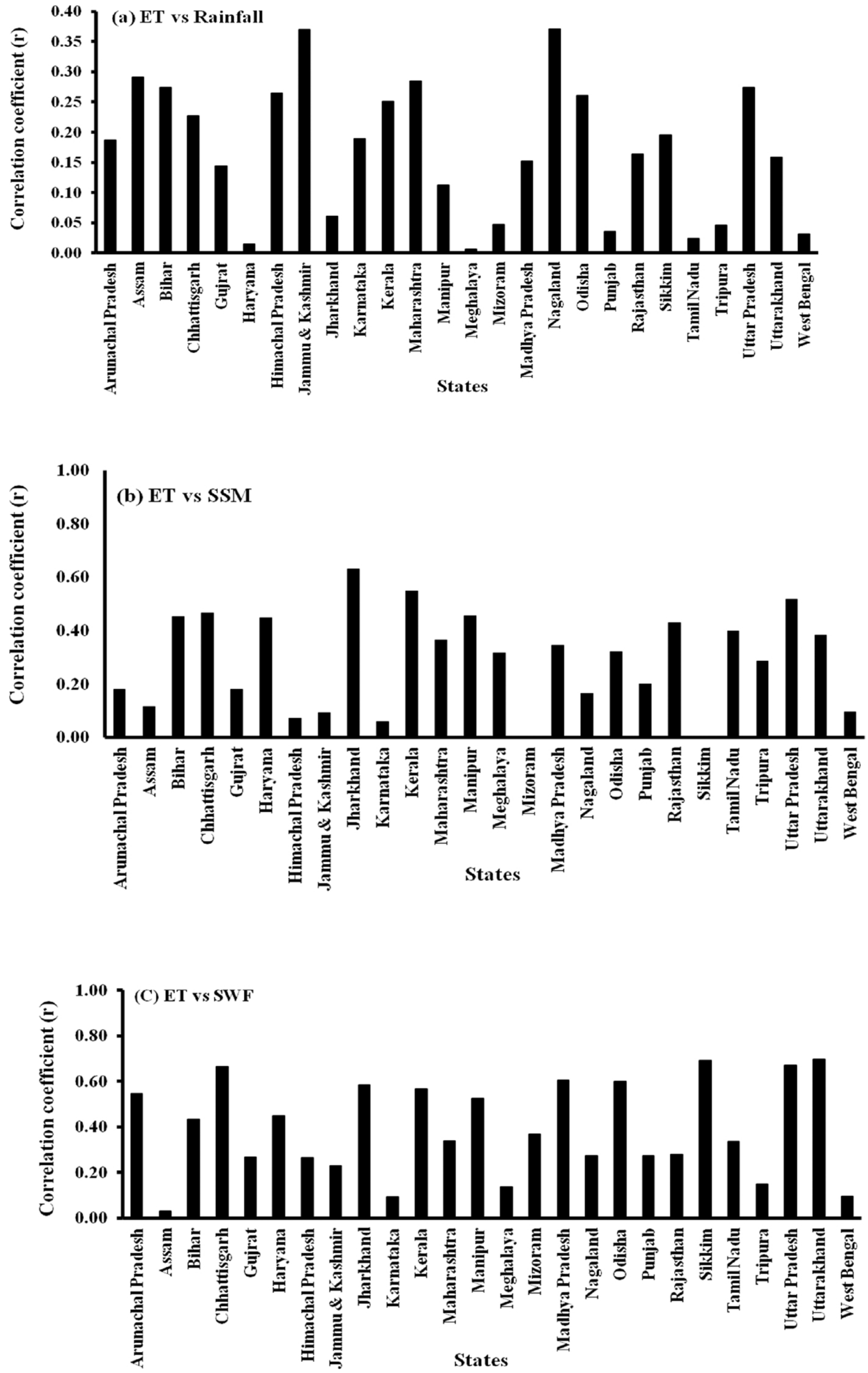

Fig. 11. Correlation of ET with Rainfall, SSM and SWF.

Region-specific correlation between annual ET and SWF was found to have highest range (0.1-0.75) followed by ranges of 0.1- 0.6 and of 0.05-0.35 between ET and SSF and between ET and rainfall, respectively. A moderate to low correlation could be due to differences in native spatial resolution between ET and other forcing variables. The gridded rainfall generated from in situ gauge measurements of sparse network through interpolation might lead to low correlation. Scatterometer has sensitivity to surface soil moisture under low vegetation cover only. This led to moderate range of correlation with ET. The SWF is reanalysis data synthesized from model simulation, satellite observations and in situ measurements. This could lead to higher correlation range with ET.

7. Conclusion

The results of the analysis are useful to understand monthly ET dynamics, climatic pattern of annual ET over different land cover types alongwith its relationship with various climatic parameters. This study brought out climatology (1981–2010) of annual loss of water through ET from Indian vegetation with 30 years' of satellite data at a spatial resolution finer than existing climatic ET generated at global scale. This has been accomplished using simplified single-source energy balance, tower-based India-specific scaling functions and time series optical-thermal remote sensing data from NOAA and MODIS corrected with respect to in situ micrometeorological measurements. Both MODIS and

NOAA ET data have been compared for a common year and mean deviations were found to be less than -8% with less than -2% deviation over cropland.

Water consumption patterns of major vegetation land cover types have also been identified for whole Indian region especially consumption patterns over irrigated and rainfed cropland separately in the recent decade. The climatology of annual ET over major land cover types showed lowest over grassland and highest over cropland. The declining ET trend up to 1995 followed by increase contradicts the accelerated water cycle predicted from climate models. The natural forcing factors such as rainfall and solar dimming could be responsible for declining ET trend upto 1995. Irrigated croplands showed steep increase trend in water consumption pattern during 2001–2010 while rainfed cropland systems showed no significant trend. Crossover points were noticed between increasing water consumption pattern of irrigated cropland and declining water consumtion patterns of grassland and forest at the later part of 2001–2010.

The analysis of region-specific annual ET showed significant trends in seven states; positive trend for Bihar, Madhya Pradesh, Maharashtra, Tamil Nadu and Himachal Pradeshand negative trend for Tripura and Mizoram. The increasing ET trend is in line with increasing rainfall and SSM trends in Maharashtra and Tamil Nadu while increasing ET was noticed in Bihar and Madhya Pradesh without significant trend in rainfall. Decreasing ET trend in two hilly NE states are opposite to rainfall trend. No significant trend was noticed over those states for surface insolation. The anomalous ET trend pattern with respect to natural water-supply factors triggered the need for detailed investigation of the role of anthropogenic factors on land ET over Indian subtropics. Shortwave radiation flux showed higher range of correlation with region-specific annual ET followed by surface soil moisture and rainfall with ET.

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